VEHICLE DYNAMIC MODELING AND SIMULATION: COMPARING A FINITE-ELEMENT SOLUTION TO A MULTI-BODY DYNAMIC SOLUTION

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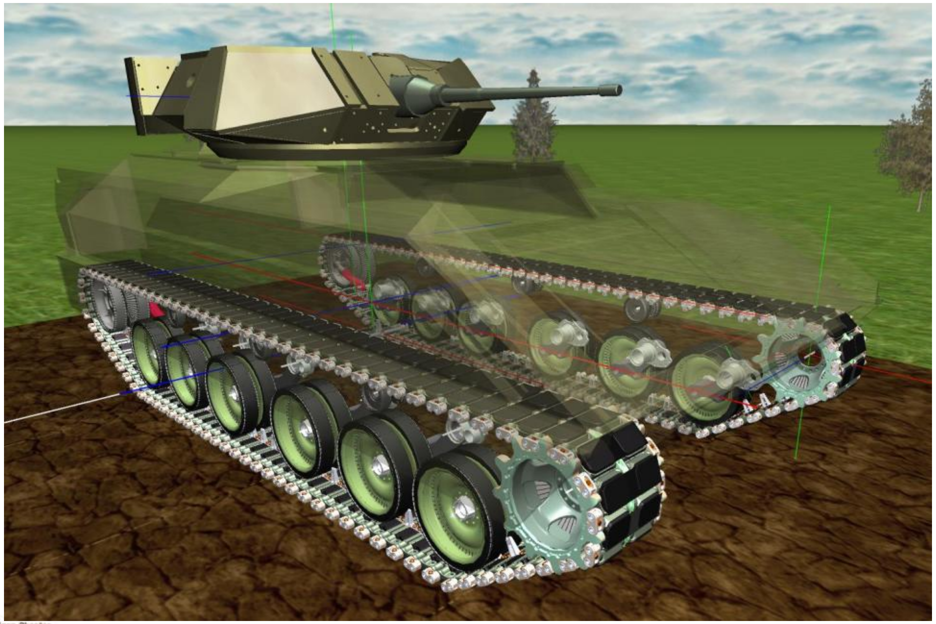
Motivation

- Army needs high-fidelity multibody dynamic modeling of wheeled and tracked vehicles for predicting:
  - Stability (going over a rough terrain at high-speed, lane change, etc.)
  - Mobility analysis (going over bumps and potholes).
  - Fatigue life and durability of various vehicle components.



Motivation (cont.)

- Two modeling and simulation approaches:
  - Traditional solution: Rigid/Flexible Multibody Dynamics (MBD) codes.
  - Alternate solution: Explicit Finite Element (FE) codes.

- Advantages of Explicit FE codes over MBD codes.
  - Multi-physics modeling such as fluid-structure interaction or thermal effects.
  - Same software environment to model flexible bodies and to predict stresses
    - However, accurate stress analysis requires refined mesh and takes significantly more CPU time.
  - Easily accommodate nonlinear material characteristics such as plasticity and fracture.
  - Can be easily parallelized.
  - Simulation time increases linearly with the DOFs.

Motivation (cont.)

- Disadvantages of explicit FE codes over MBD codes.
  - Most explicit FE codes use an incremental updated-Lagrangian solution formulation which can lead to solution drift.
  - Use inexpensive finite elements that use spurious modes control.
  - Calculated joint reaction forces exhibit high-frequency oscillations. MBD codes, on the other hand, produce accurate joint forces.
  - Integration time step (Δt) must be less than a critical time step for stability.
    - This requires a very small time step for stiff systems. MBD codes, on the other hand, can use implicit integrators that allow larger time steps.

Objective

- Benchmark the two modeling and simulation approaches.
  - Multibody dynamic code.
  - Explicit finite element code.
- Benchmark using two multibody dynamic systems.
  - A 7-link planar mechanism.
  - A spatial robotic manipulator.
- Comparisons are made of:
  - Body motion.
  - Joint constraint forces.
  - Conservation of energy.
  - CPU time.
- Conclusions are drawn regarding solution accuracy and efficiency of the two codes.

Explicit FE Code Formulation

- Equations of motion:

$$M_K \ddot{x}^t_{Ki} = {F_s}^t_{Ki} + {F_a}^t_{Ki}$$

$$I_{Kij} \ddot{\theta}^t_{Kj} = {T_s}^t_{Ki} + {T_a}^t_{Ki} - \left(\dot{\theta}^t_{Ki} \times (I_{Kij} \dot{\theta}^t_{Kj}) \right)_{Ki}$$

- Integrated using trapezoidal explicit integration formula:

$$\dot{x}^t_{Kj} = \dot{x}^{t-\Delta t}_{Kj} + 0.5\,\Delta t\,(\ddot{x}^t_{Kj} + \ddot{x}^{t-\Delta t}_{Kj})$$

$$x^t_{Kj} = x^{t-\Delta t}_{Kj} + 0.5\,\Delta t\,(\dot{x}^t_{Kj} + \dot{x}^{t-\Delta t}_{Kj})$$

$$\dot{\theta}^t_{Kj} = \dot{\theta}^{t-\Delta t}_{Kj} + 0.5\,\Delta t\,(\ddot{\theta}^t_{Kj} + \ddot{\theta}^{t-\Delta t}_{Kj})$$

$$\Delta\theta^t_{Kj} = 0.5\,\Delta t\,(\dot{\theta}^t_{Kj} + \dot{\theta}^{t-\Delta t}_{Kj})$$

$$R^t_K = R^{t-\Delta t}_K\, R(\Delta\theta^t_{Ki})$$

$d_i = x_{p1}{}_i^t - x_{p2}{}_i^t$

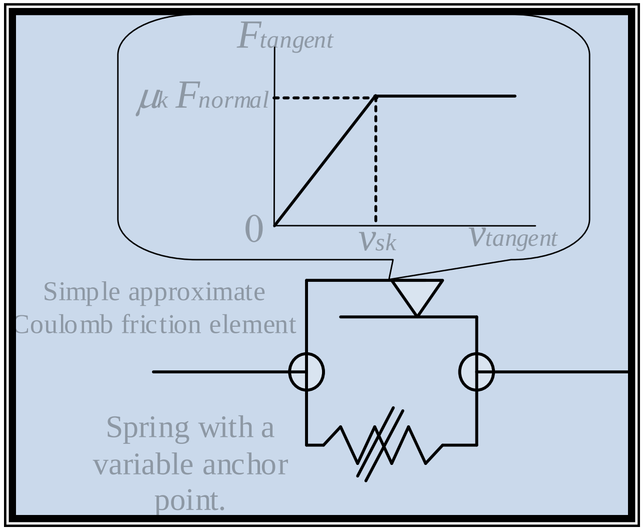
Explicit FE Code Formulation

- Constraint modeling.
  - Penalty formulation for modeling normal contact/joint forces.

$$F_{c_j} = (k_p |\vec{d}| + c_p \, \hat{d}_i \dot{d}_i) \hat{d}_j$$
$$d_i = x_{p1}{}_i^t - x_{p2}{}_i^t$$

where k_p: penalty stiffness, c_p: penalty damping

- Friction model.
  - Asperity-spring friction model is used to model joint and contact friction.



$\dot{d}_i^t = \dot{x}_{p1}{}_i^t - \dot{x}_{p2}{}_i^t$

Multibody Dynamic Code Formulation

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

- Equations of motion :

$$\begin{bmatrix} M & \dfrac{\partial \Phi}{\partial q}^T \\ \dfrac{\partial \Phi}{\partial q} & 0 \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \lambda \end{Bmatrix} = \begin{Bmatrix} Q \\ \gamma \end{Bmatrix}$$

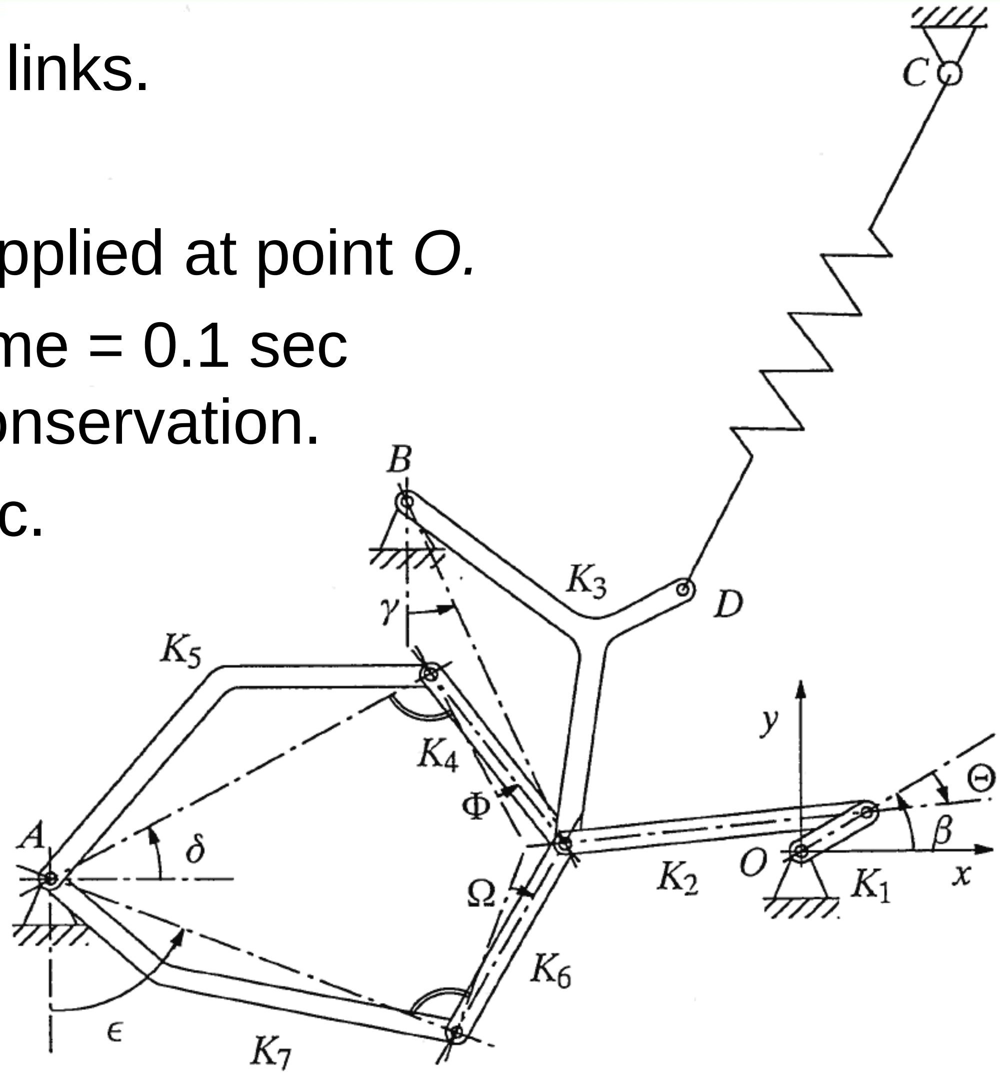
- Constraint equations:

$$\Phi(q,t) = 0 \qquad \frac{\partial \Phi}{\partial q}\dot{q} = \nu$$

- Forms a set of Differential-Algebraic Equations (DAEs).
- Solved using implicit integration methods such as the Backward Differentiation Formula.
  - Can take much larger time step than explicit methods.
  - Very advantageous for stiff systems.
  - Time step is only dictated by desired solution accuracy.

Benchmark Problem 1: 7-Link Planar Mechanism

- 2D mechanism with 7 rigid links.
- 1 DOF system.
- Driven by a motor torque applied at point *O.*
  - Torque is removed at time = 0.1 sec to assess the energy conservation.
- Total solution time = 0.5 sec.



Benchmark Problem 1: 7-Link Planar Mechanism

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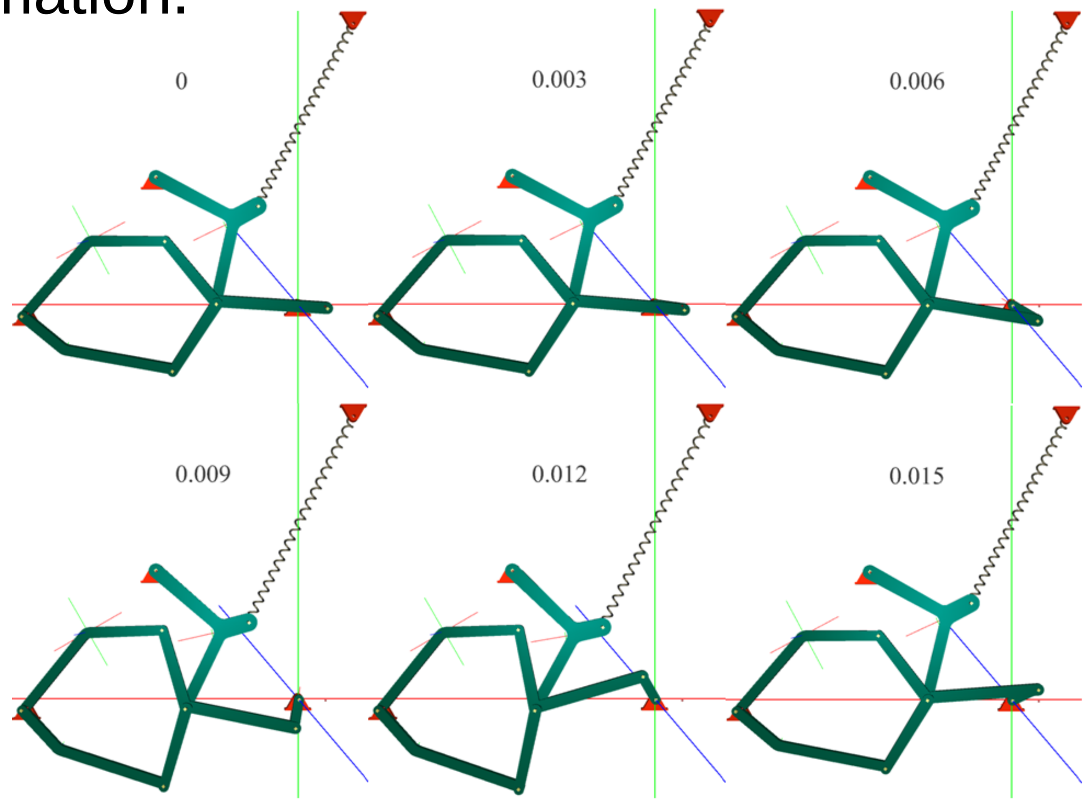
- Time step / CPU time comparison.

	MBD	FE	FE
Time step (s)	1.0E-5	0.4E-5	0.1E-5
CPU time (s)	20.875	4.955	19.820
Position/velocity error Tolerance	1E-3	-	-

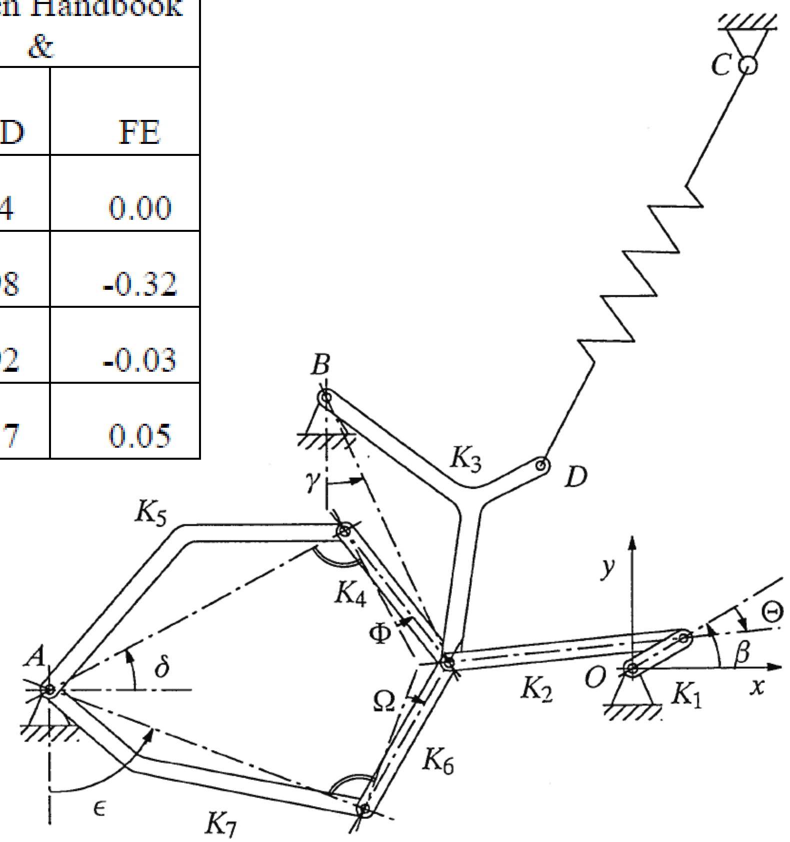
- Animation.



Benchmark Problem 1: 7-Link Planar Mechanism

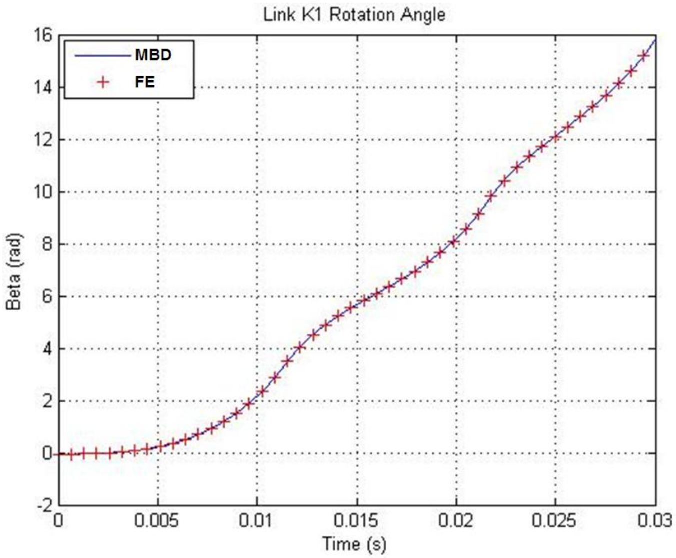
- Link K1 rotation angle comparison.

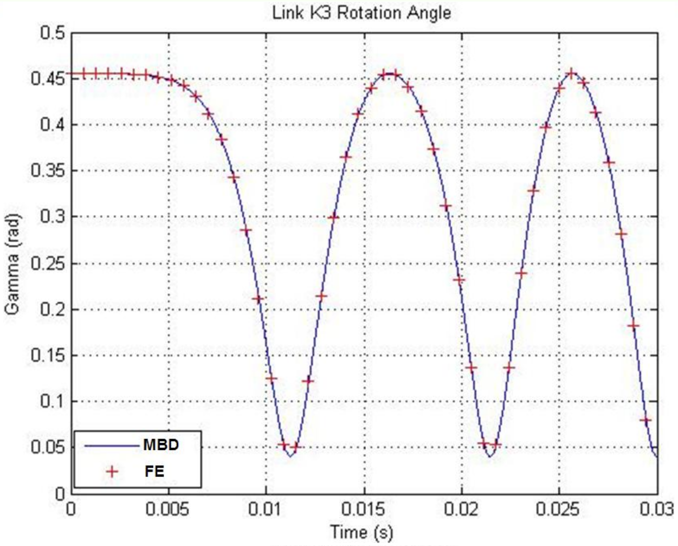
Time (s)	Beta (rad)			% Difference between Handbook &	
	Handbook [3]	MBD	FE	MBD	FE
0.000E+00	-6.1994E-02	-6.2017E-02	-6.19953E-02	0.04	0.00
5.000E-03	2.10881E-01	2.06715E-01	2.10215E-01	-1.98	-0.32
1.000E-02	2.16040E+00	2.14057E+00	2.15981E+00	-0.92	-0.03
1.500E-02	5.65556E+00	5.64598E+00	5.65841E+00	-0.17	0.05

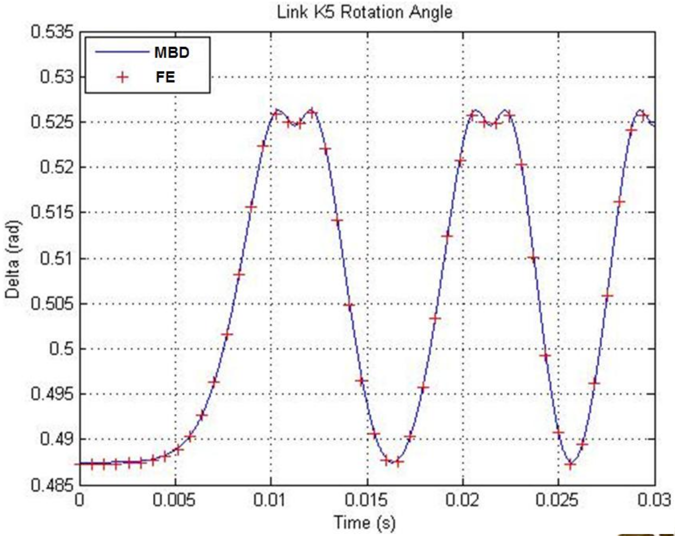


Benchmark Problem 1: 7-Link Planar Mechanism

- Link rotation angles comparison

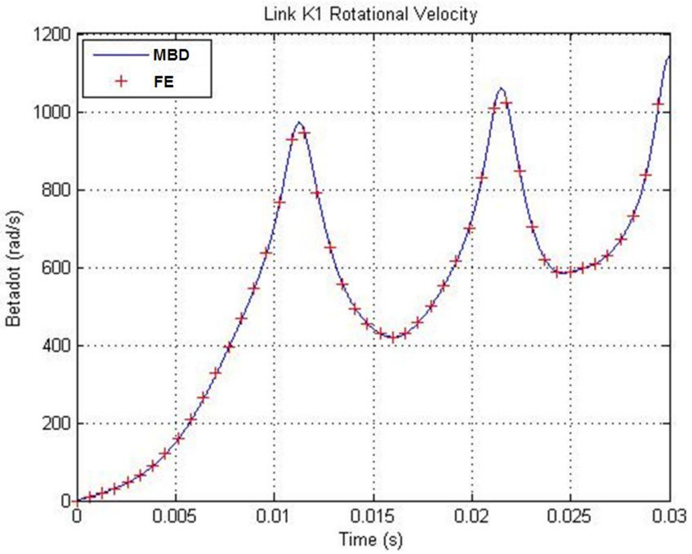


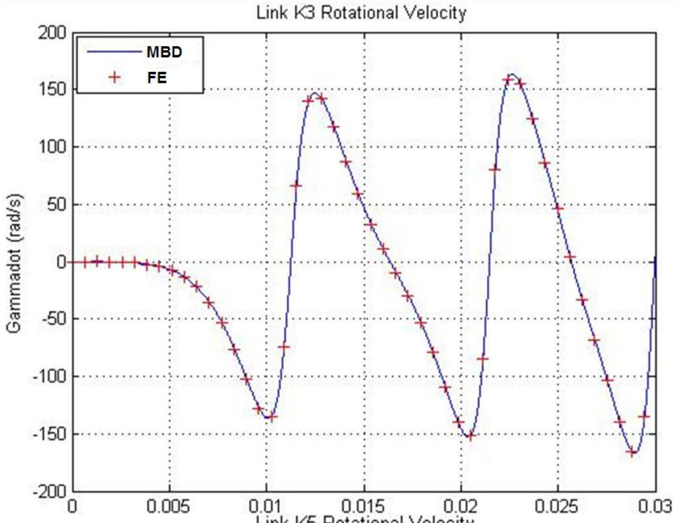


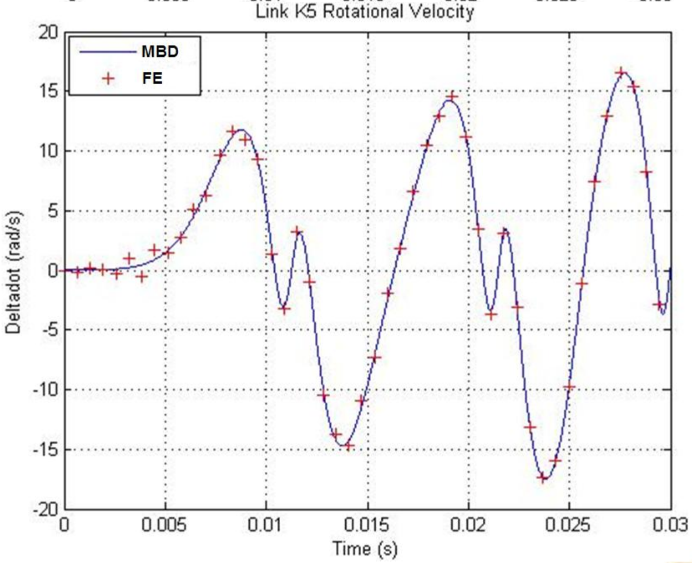


Benchmark Problem 1: 7-Link Planar Mechanism

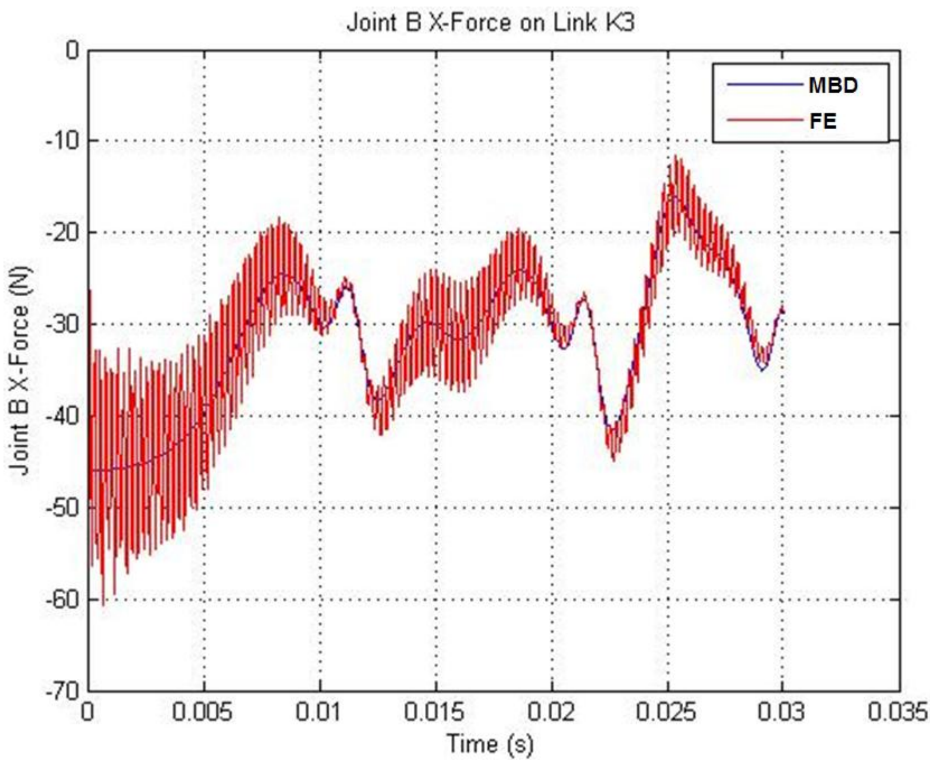
- Link velocities comparison.

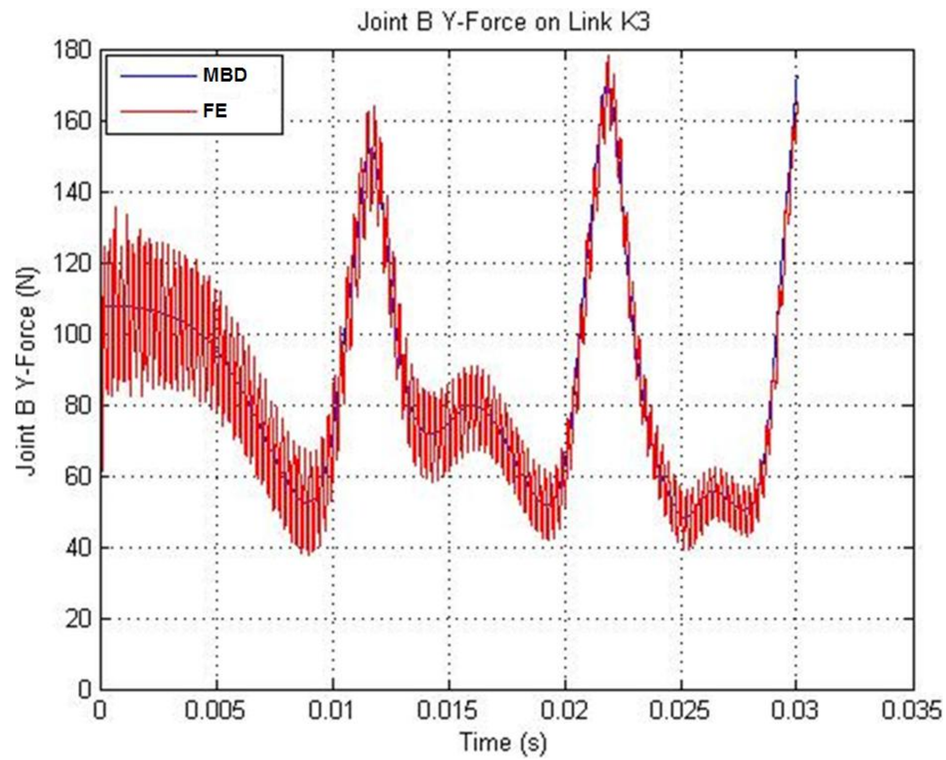






- Joint force comparison.





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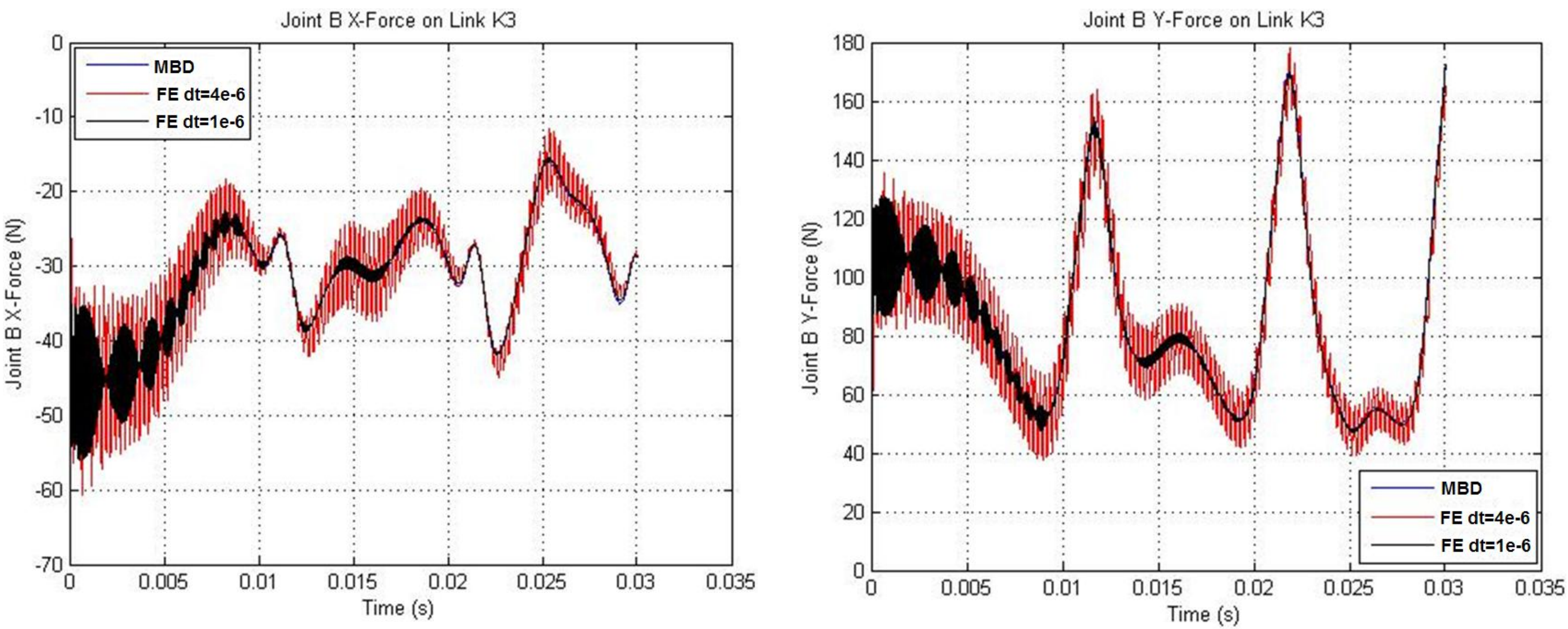
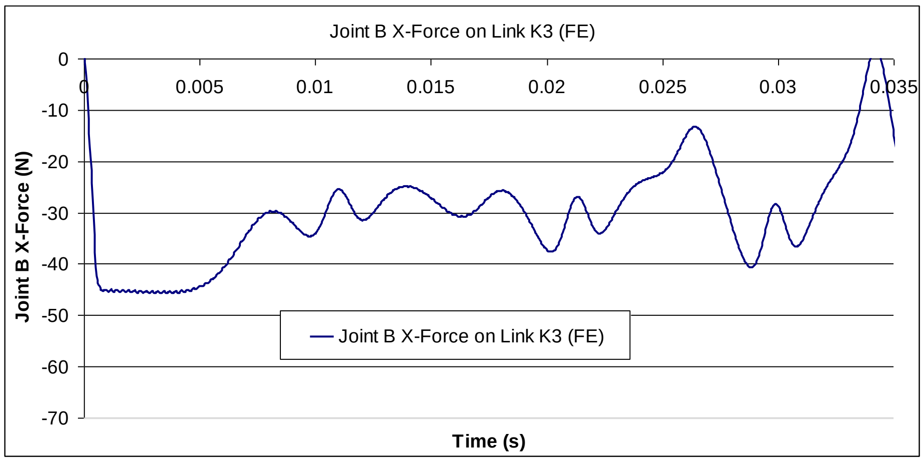
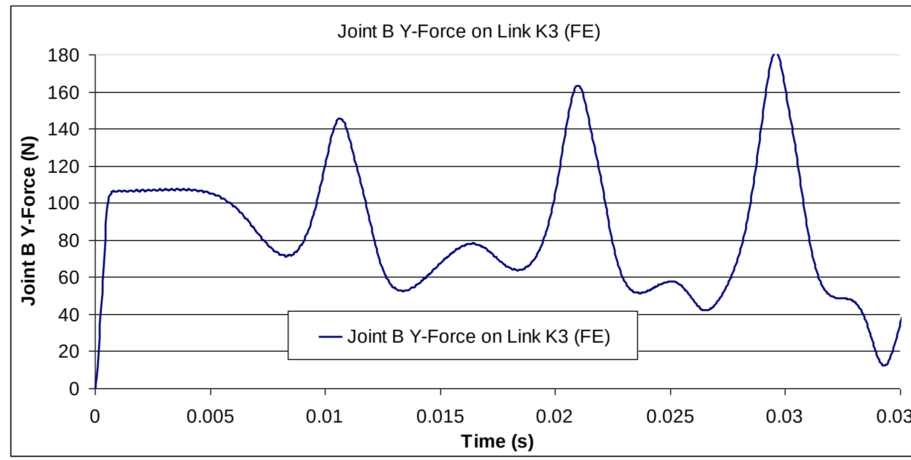
- Effect of FE time step on joint forces.



Benchmark Problem 1: 7-Link Planar Mechanism

- FE joint force with ramped applied torque and spring pre-load.





FE: Δt = 0.4E-5

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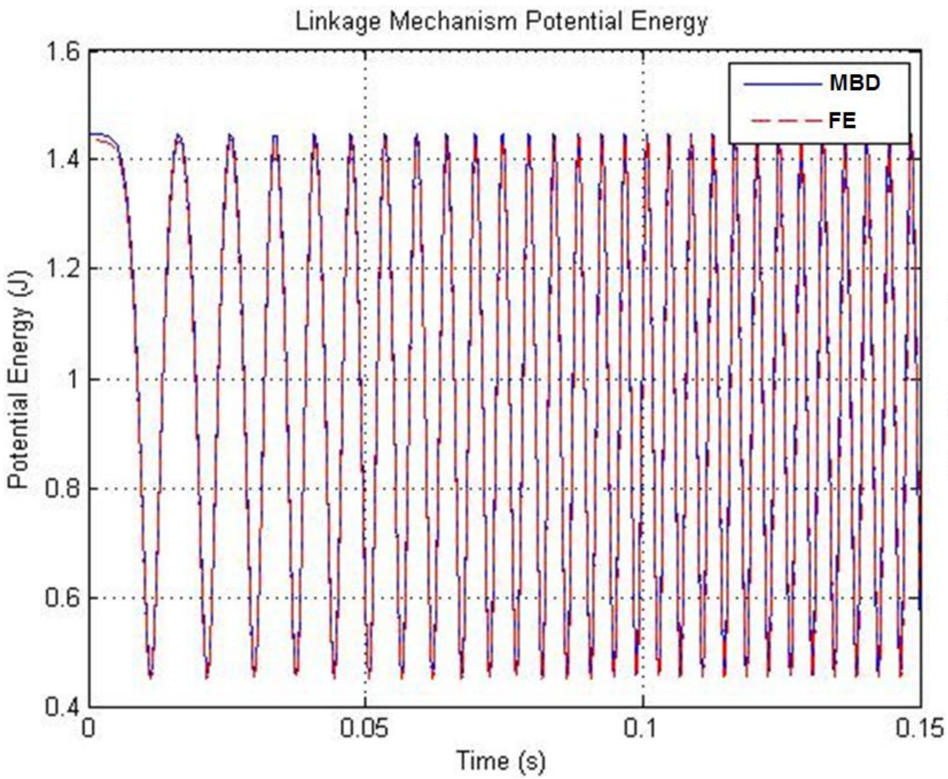
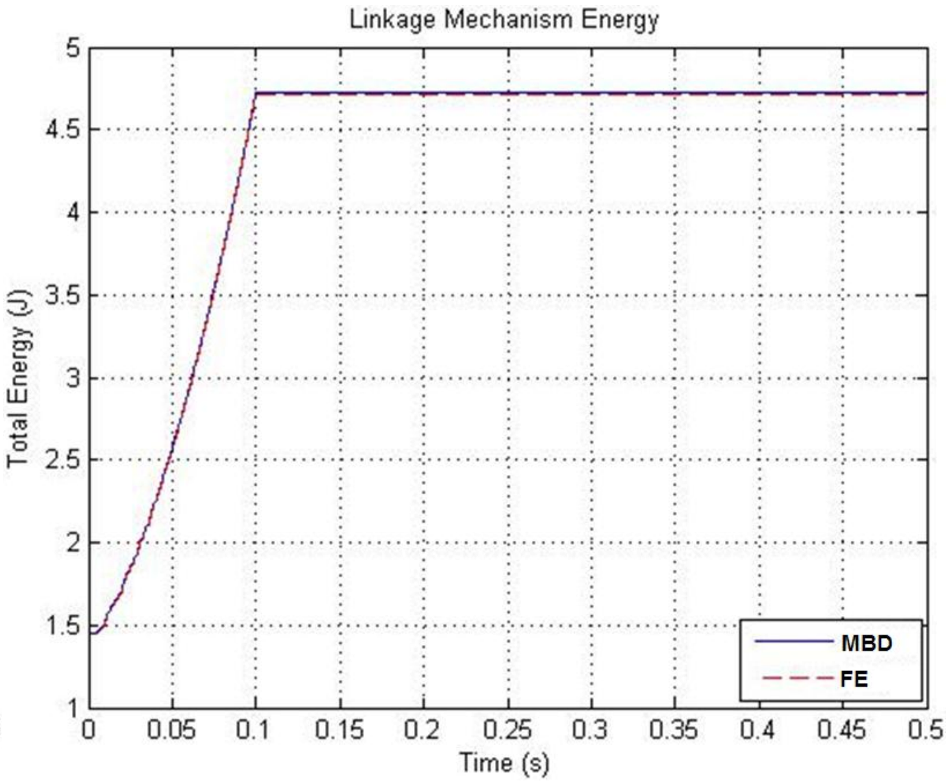
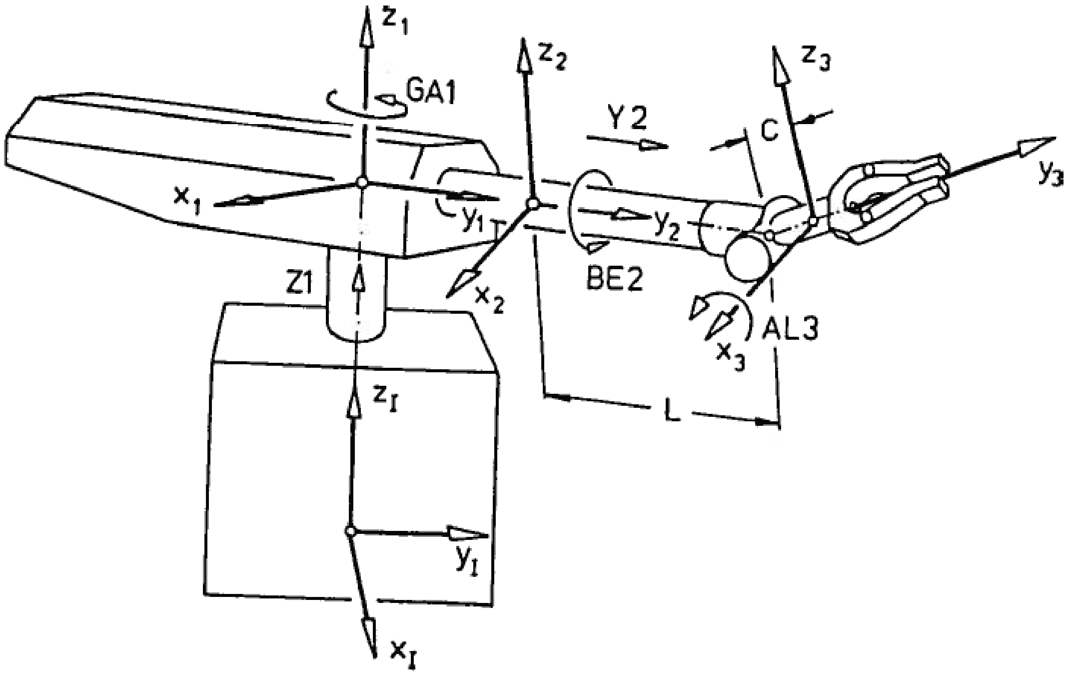
- Energy comparison.





Benchmark Problem 2: Spatial Robotic Manipulator

- 3 rigid bodies connected using cylindrical and revolute joints.
- 5 DOF system.
- External loads: gravity and prescribed joint actuator forces/torques.
- End effector traces a straight line with a trapezoidal velocity profile.
- Total solution time = 2.0 sec.

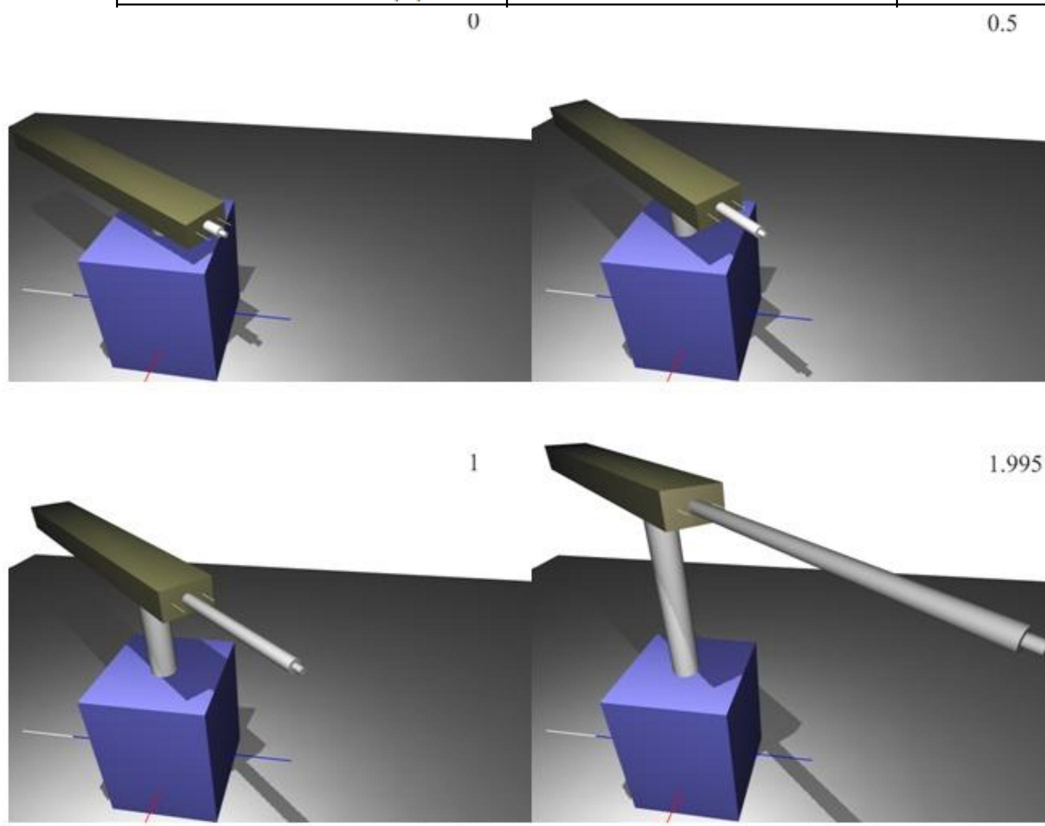


Benchmark Problem 2: Spatial Robotic Manipulator

- Time step / CPU time comparison.

	MBD	FE
Time step (s)	0.01	3.75E-5
CPU time (s)	0.172	1.29

- Animation.



Benchmark Problem 2: Spatial Robotic Manipulator

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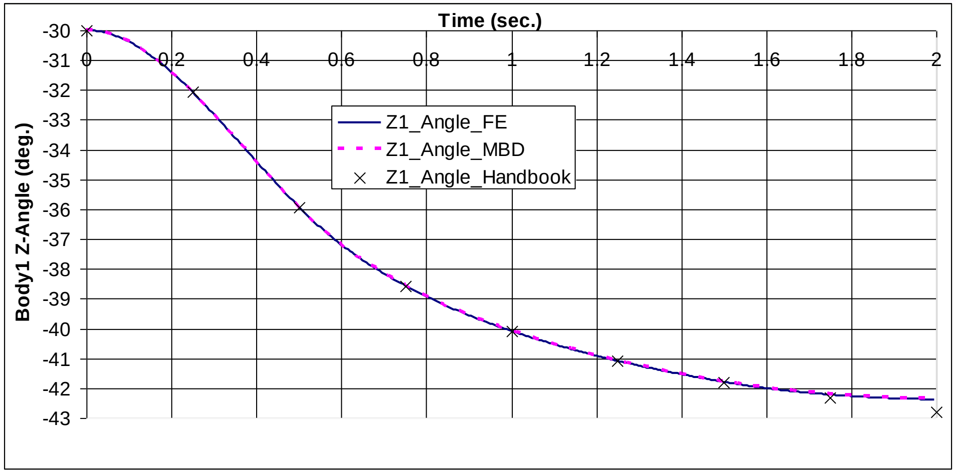
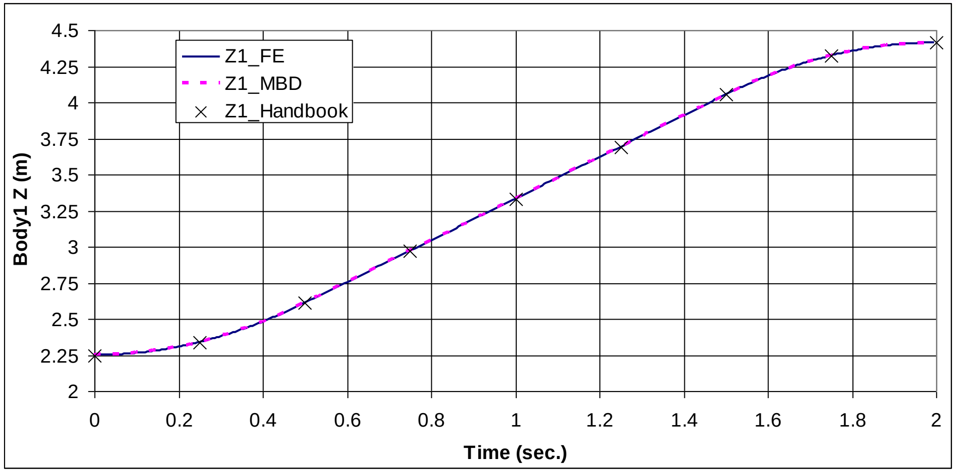
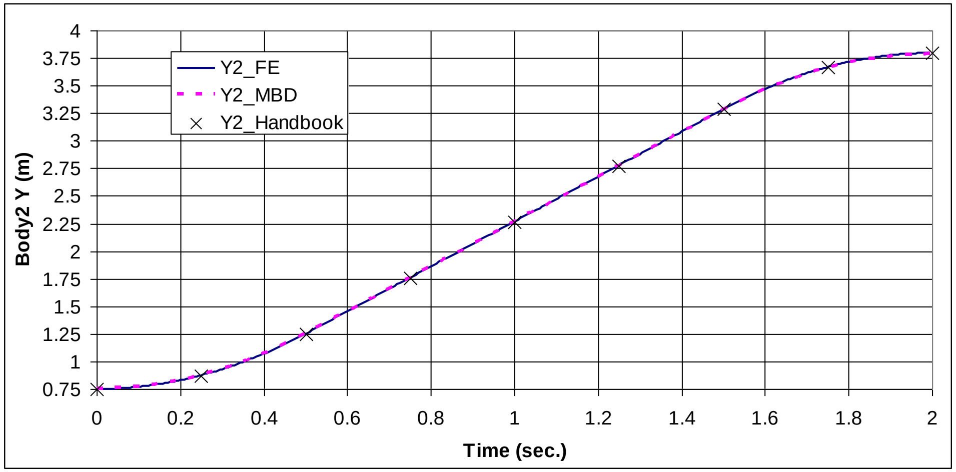
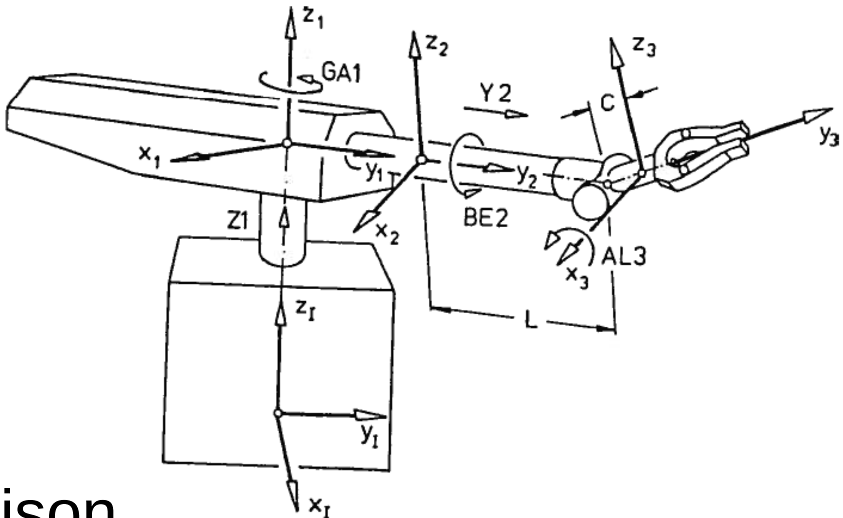


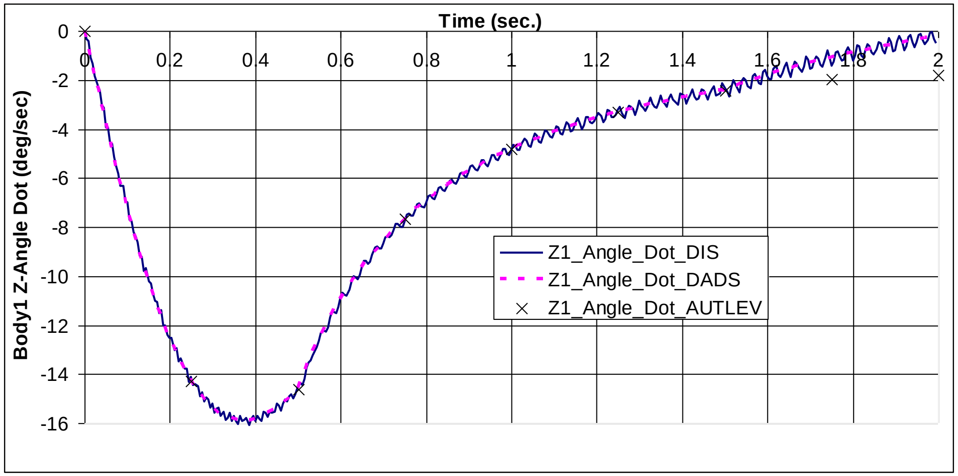


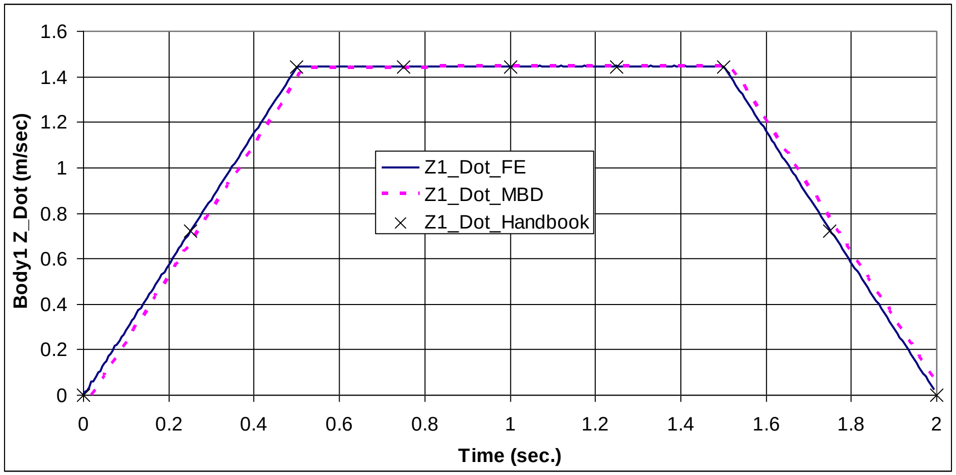


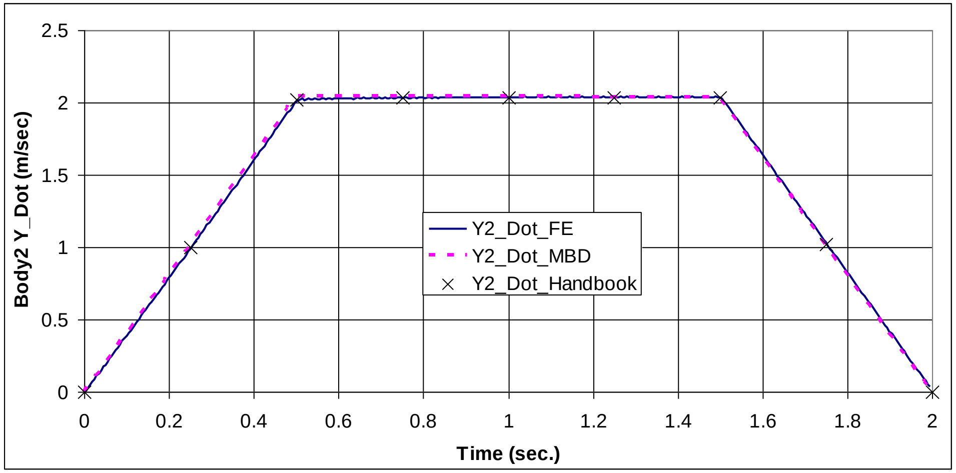


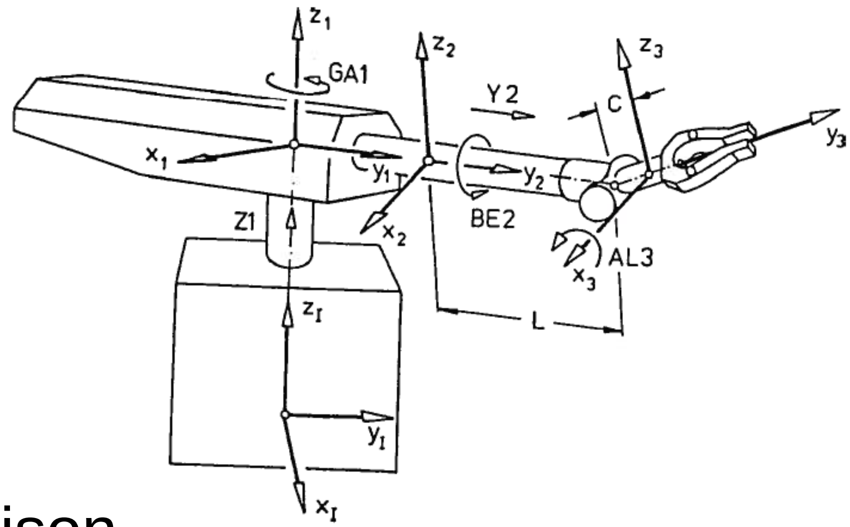
- Manipulator Position Comparison

Benchmark Problem 2: Spatial Robotic Manipulator



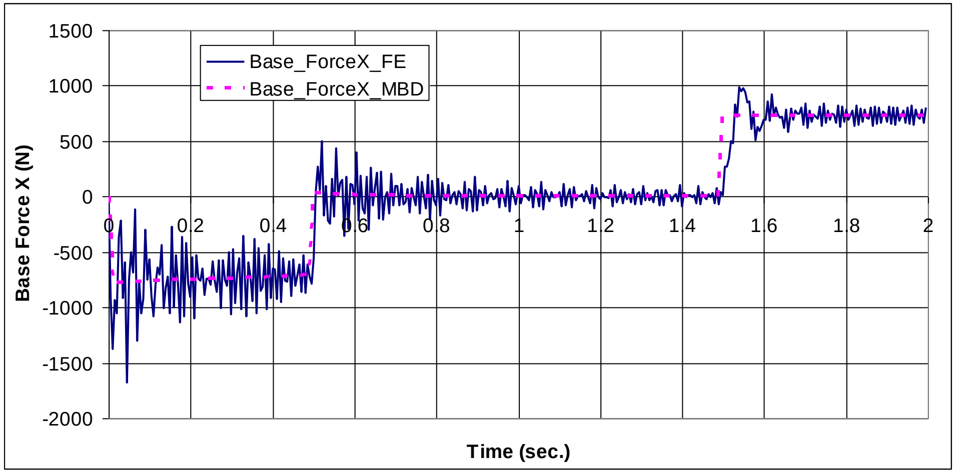


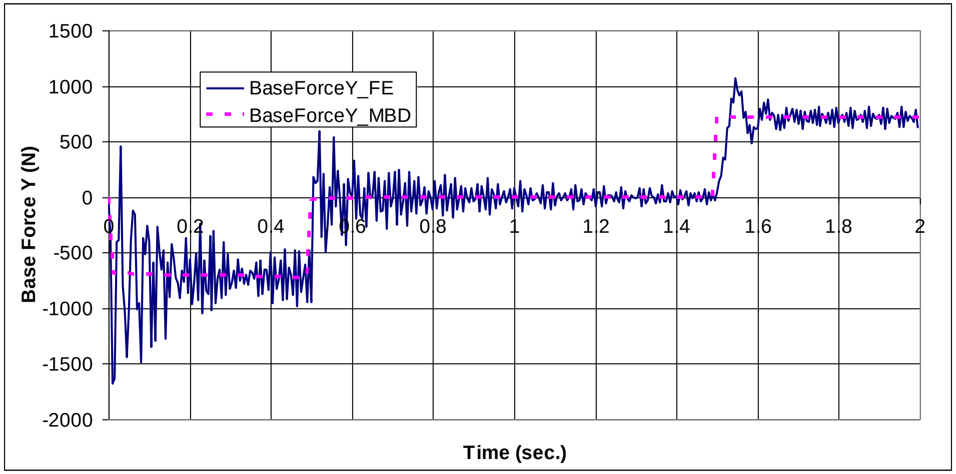


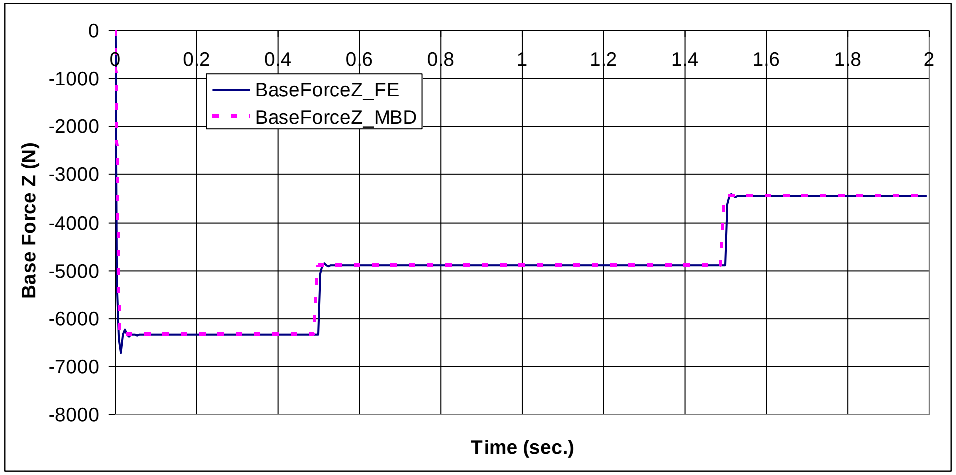


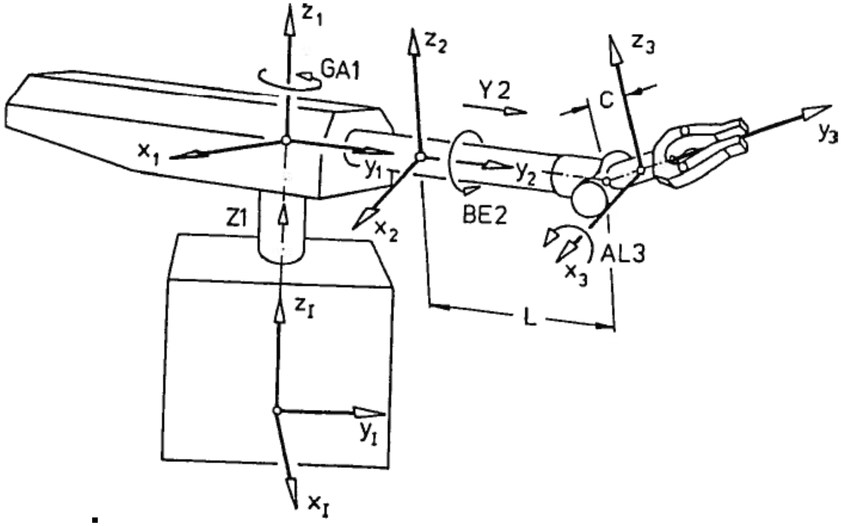
- Manipulator Velocity Comparison

Benchmark Problem 2: Spatial Robotic Manipulator









- Manipulator Joint Force Comparison

Conclusions

- Two multibody dynamics benchmark problems were solved using
  - an explicit finite-element code and
  - an implicit multibody dynamics code.
- The two codes predict the same system motion.
- Joint reaction forces predicted by FE code have high-frequency oscillations due to the penalty method used.
- To eliminate high-frequency force oscillations when using FE code, applied forces/moments must be continuous and the simulation should start from static equilibrium.
- Implicit MBD codes are computationally more efficient than Explicit FE codes for stiff MBD systems.